DESIGN AND CONTROL OF THE MESUR/PATHFINDER MICROROVER

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ABSTRACT

The use of unmanned robotic vehicles to assist in the exploration of Mars and other planets has been of interest to the National Aeronautics and Space Administration (NASA) for several decades and has been the focus of an ongoing research program at the Jet Propulsion Laboratory (JPL) for a similar period of time. As a result of these research activities, JPL is in the process of designing and building a small (7-9 Kg) microrover to be flown aboard the MESUR/Pathfinder [1] spacecraft which is tentatively due to be launched to Mars in December of 1996. The lander portion of the spacecraft, which contains the microrover, will perform a variety of technology experiments designed to provide information critical to the design of future planetary probes. In addition, the microrover will perform several science and lander related experiments using specialized onboard instruments. To enable the microrover to perform these experiments at selected target areas and at the same time deal with the long time delays (and limited communications bandwidth), a control/navigation approach combining the use of operator designated waypoints and onboard behavior control has been adopted. The design of the MESUR/Pathfinder microrover and the overall manner in which it is controlled are described herein.

1 BACKGROUND

For many years, JPL and NASA have been developing mission concepts for the continued exploration of Mars. The most recent outcome of this activity has been a proposal to fly two separate but related missions, the first being the MESUR/Pathfinder Mission and the second being the MESUR/Network Mission. The MESUR/Pathfinder Mission, which is currently scheduled to launch in December of 1996, will be used to demonstrate and evaluate the performance of a low cost MESUR-like spacecraft. The spacecraft will be evaluated on its ability to deliver a lander to the martian surface, withstand and reliably operate within the martian environment, support scientific instruments, and perform experiments. MESUR/Pathfinder will be NASA's first low cost "Discovery" claw mission [2].

The MESUR/Pathfinder spacecraft will also deliver a Microrover to Mars [3]. (The MESUR/Pathfinder microrover is based on the Rocky III and Rocky IV vehicles developed previously at JPL as part its robotics research activities [1].) The primary objective of this component of the mission will be to demonstrate and evaluate the performance of a low-cost, MESUR-like microrover and to characterize its interaction with the martian environment (e.g., soil, atmosphere, etc). The ability to detect and avoid hazards, navigate to desired target locations based upon measurements from onboard sensors and high level commands from ground-based operators, drive across terrain with varying soil and rock properties, and perform useful scientific tasks are critical features to be tested and demonstrated. Figure 1 depicts the basic configuration of the MESUR/Pathfinder lander and microrover.

In contrast to the MESUR/Pathfinder Mission, the MESUR/Network Mission will involve the delivery of up to 16 low-cost landers to Mars and will focus on performing a wide range of scientific experiments involving measurements taken from widely distributed landing sites (i.e., > 100 Km apart). The primary objectives of the mission are to determine the global seismicity and internal structure of Mars; to improve our knowledge of the global circulation within the atmosphere and of meteorological conditions at the surface; and to determine the elemental chemistry, mineral composition, and ice content of near-surface soils and rocks. Network's configuration also provides data essential for planning future manned missions.

The first launch of the MESUR/Network Mission is scheduled for 1999.

[1] Mars Environmental SURvey Mission (MESUR)

[2] The cost of a Discovery Class Mission capped at $150 (US)

[3] The microrover is separately funded by NASA's research program (Code C). Its cost is not included in the MESUR/Pathfinder's $150M Cost Cap).

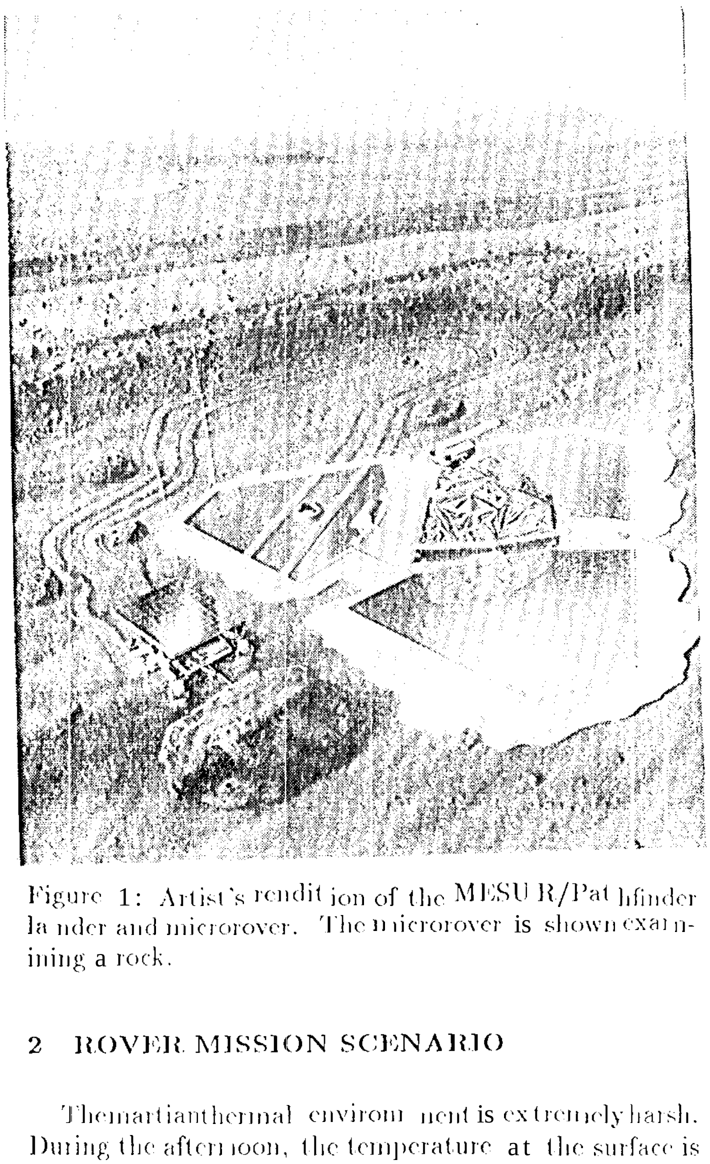

Figure 1: Artist's rendition of the MESUR/Pathfinder lander and microrover. The microrover is shown examining a rock.

2 ROVER MISSION SCENARIO

The martian thermal environment is extremely harsh. During the afternoon, the temperature at the surface is expected to be around 25C, whereas at night, the temperature will drop to as low as -125C. Such variations pose a significant threat to the survivability of the rover as well as the lander. In response to this, the surface operations plan has been divided into two components, the Primary Mission and the Extended Mission. The Primary Mission is currently scheduled to last for 7 Sols[4]. The objective of the Primary Mission will be to perform each of the 1('11 baselined technology experiments at least once, collect a APXS spectrum of a rock, and acquire an image of the lander in the least number of thermal cycles (i.e., Sols). During the Primary Mission, the microrover will remain within the view of the lander's cameras and travel anywhere from 10 to 100 meters.

The Extended Mission begins on the 8^{th} Sol after which the same experiments will be performed over a wider range of terrain/environmental conditions. Additional APXS spectra and images of the lander will also be taken. If it survives, the microrover will also be commanded to explore beyond the lander's visual horizon and potentially beyond the range within which the microrover and lander can communicate. The latter is estimated to be at about 700 meters and would naturally require the microrover to return periodically to transmit data. (It should be noted that nothing within the microrover's design precludes it from operating indefinitely.)

[4] 1 Sol = 1 martian day = 24 hours, 40 minutes (i.e., slightly longer than 1 earth day)

3 VEHICLE DESIGN

The MESUR/Pathfinder microrover system is comprised of the following four subsystems:

- Mobility
- Control and Navigation
- Power
- Telecommunications

The Mobility subsystem includes the vehicle chassis, wheels, wheel drive and steering mechanisms (i.e, motors, gears, encoders); the rocker-bogie suspension system; the Warm Electronics Box (WEB); the solar panel substrate; rover-to-lander mounting hardware; and various internal subchassis (e.g., battery box). The Control and Navigation Subsystem includes the onboard CPU, memory, and I/O electronics boards; the onboard navigation sensors (e.g., cameras, accelerometers, etc.); all onboard software; the rover ground control station; and the ground control station software. The Power subsystem provides the solar cells for the solar panel, the battery cells, and a regulator board containing a variety of DC/DC power converters. The Telecommunications subsystem consists of the two UHF modems and whip antennaes, one for the lander and one for the rover.

The basic configuration of the flight system is illustrated in Figure 2. The vehicle, shown in its deployed configuration, is 65.0 cm long, 48.0 cm wide, and 30.0 cm high, and will have a mass of between 7-9 Kg. When stowed in the lander during cruise, the rover is only 18 cm high.

3.1 Mobility Subsystem

One of the key features depicted in Figure 2 is the rocker-bogie suspension system [2]. This suspension system gives the vehicle an exceptionally high degree of mobility enabling it to travel across fine dust, and climb obstacles twice the diameter of its wheels. The design consists of two identical but independent planar linkage mechanisms,

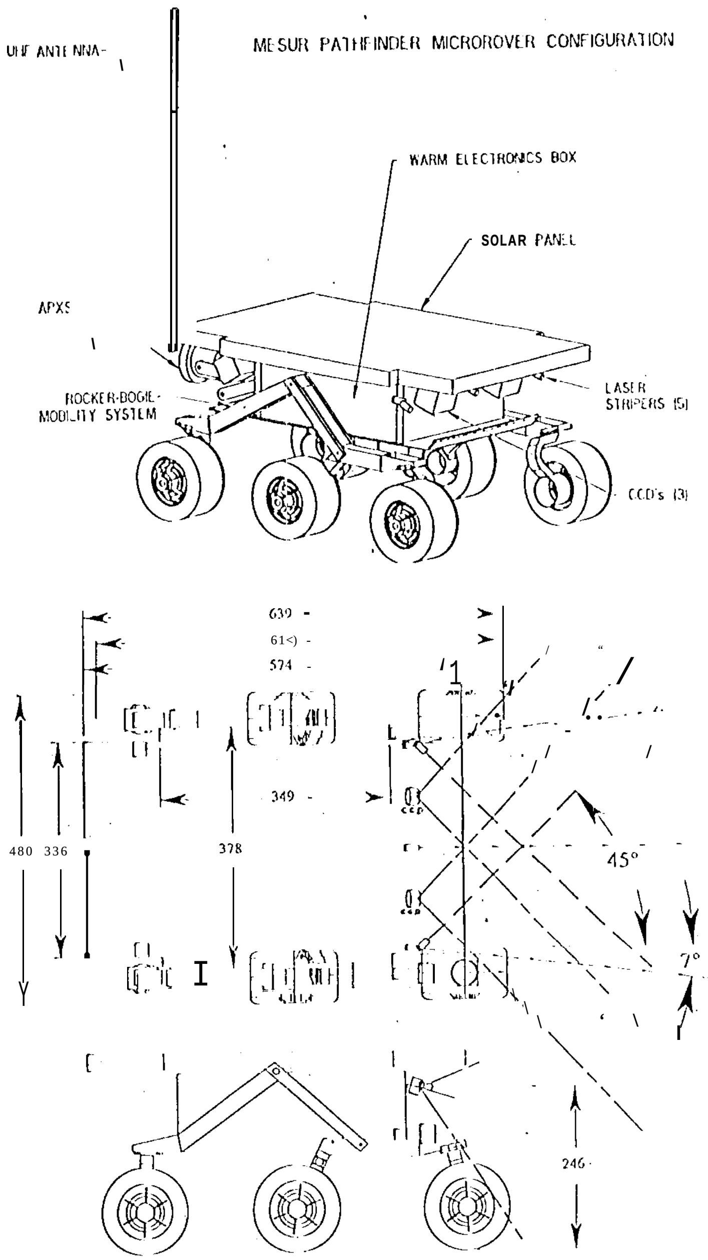

Figure 2: Schematics of the MESUR/Pathfinder Microrover showing the relative placement of the six drive wheels, the rocker-bogie suspension system, the Warm Electronics Box (WEB), the two forward looking cameras, the five laser stripe projectors, and the solar panel.

one on either side of the vehicle, interconnected to the vehicle chassis by a differential. The differential constrains the chassis such that the relative rotation between either rocker and the chassis is half that of the rotation between

Table 1 Onboard sensors

Qty	Sensor	Primary Function(s)
(3)	Accelerometers	Hazard Detection
(1)	Rate Gyro	Dead Reckoning
(4)	Bumper (chassis)	Collision Detection
(4)	Bumper (solar)	Collision Detection
(2)	CCDs (front)	Imaging; Proximity
(1)	CCDs (rear)	Imaging; Target Validation
(3)	Temp (CCDs)	CCD Calib.;Scientific Imaging
(2)	Temp (Motor)	Motor Performance Evaluation
(3)	Temp (WEB)	Thermal Control & Characterization
(3)	Temp (Solar)	Array Performance Evaluation
(2)	QCM [5]	Dust Adherence;Particle Mass
(2)	Solar Cells	Power Management
(6)	Current (Motor)	Torque Monitoring; Fault protection
(3)	Current (Batt)	Power Management
(5)	Current (Reg)	Power Management
(2)	Bogie Position	Hazard Detection; Mobility
(1)	Differential Pos.	Hazard Detection; Mobility
(6)	Wheel Position	Dead Reckoning
(4)	Steering Angle	Direction Control
(10)	Voltage (Motor)	Motor Performance Evaluation
(1)	Solar Cell	Wheel Abrasion
(4)	Separation	Deployment State
(1)	APXS Position	Deployment Control
(3)	Bumper (APXS)	APXS Emplacement
(3)	Real-Time Clock	Time/Alarm Clock

the two rockers. Other important features of the rocker-bogie design include the statically deterministic loading of the vehicle's weight on the wheels, a nominal ground pressure of 0.5 psi (on Mars), and the absence of kinematically induced tracking errors. The latter is due to the fact that the wheels are constrained by the mechanism to remain in plane.

Control of the vehicle's orientation is achieved by changing the orientation (i. e., steering angle) of the four corner wheels. Since the steering angles are independently controlled, the vehicle can turn about any radius including zero (i. e., to turn in place) without skidding. Although the vehicle is mechanically capable of true Ackermann steering, a slightly simpler algorithm is used to reduce the complexity of the control system. The simplification involves setting the speed of the six drive wheels to the same value as opposed to the true Ackermann values. In practice, this only affects the vehicle's performance and the accuracy of the dead-reckoning algorithm during tight turns. The ability to turn in place without skidding, however, overcomes this limitation.

3.2 Control and Navigation Subsystem

The microrover contains an extensive suite of sensors which are used for navigation, hazard and obstacle detection, power management, fault protection, and collection of measurements for particular technology experiments. The types of sensors and their primary function(s) are listed in Table 1. Many of the sensors serve multiple functions. For example, the three internal linear accelerometers are used 1) to measure the orientation of the chassis with respect to vertical to indicate how close the vehicle is to tipping over, 2) to measure instantaneous accelerations during traversal in support of the technology experiments; and 3) to compensate the rate gyro readings. In addition to these sensors, the micrerr-over contains an Alpha/Proton/X-Ray Spectrometer (APXS) which is attached to a deployment mechanism 011 the back of the microrover. Spectra from the APXS will be used by the scientists to measure elemental composition. The APXS will be provided by the Max Van Plank Institute in Germany and the University of Chicago in the USA.

The sensors listed in Table 1, the ten wheel motors, the APXS, the 111111' modem, and several miscellaneous actuators (i.e., nitinol dust covers, latches, etc.), are all interfaced to and controlled by a single onboard microprocessor. The microprocessor is bawd upon the 80C85 CPU which has been used extensively on other planetary spacecraft, is fully flight qualified, and immune to Single Event Latchups (SELs). The 80C85 is a 100 Kips, 8 bit machine with a 16 bit address space (i. e., 64Kbyte address space). Bank switching will be used to extend the onboard memory to 672 Kbytes (16 Kbytes of core ROM, 16 Kbytes of core RAM, 1 28Kbytes of Flash EEprom, and 512Kbytes **of** bulk RAM). The bulk RAM is for storing images and engineering data prior to transmission to earth. The onboard control code is expected to occupy approximately 60-80Kbytes of the core ROM and EEPROM.

4 CONTROL AND NAVIGATION

4.1 Control Strategy

The strategy for commanding and controlling the microrover is based upon a combination of operator-based waypoint designation [3] and onboard behavior control [4, 5, 6]. The waypoint designation component deals with the ground-based planning of the activity sequence and the interactive selection of the locations through which the vehicle should travel in order to reach desired activity sites. During this step in the process of controlling the microrover, it is the responsibility of the human operator to designate paths (i.e, a sequences of waypoints) which are free of obstacles and/or hazards which could threaten the safety of the vehicle and jeopardize the mission. The behavioral component of the control strategy corresponds to the onboard algorithms which autonomously and safely navigate the vehicle from one waypoint to the next. These algorithms account for the inaccuracies involved in navigating along unknown terrain and the presence of obstacles and/or hazards which were undetected by the operator.

The task of designating a waypoint is conceptually quite simple. Using the display capabilities built into the Rover's Control Station, the operator looks at the local martian terrain in 3-D and chooses how best to get from one location to another. The 3-D images are obtained from the lander's stereo imaging system which is located approximately 1.5 meters above the ground. (The lander cameras have an imaging resolution of 1 mrad/pixel). A joystick is then used to position a **3-D** graphical model of the microrover at locations (i.e., the waypoints) which, when connected by straight lines, defines the nominal path through which the vehicle should travel. If the terrain contains numerous obstacles and/or hazards, the operator can space the waypoints relatively close to one another (e.g., 0.25 meters), whereas if the terrain is relatively benign only a few waypoints may be needed. The choice of how many waypoints to designate is up to the operator and the experiment team.

The primary advantage of the aforementioned control strategy is the inherent separation between the planning and control functions which require significant processing capabilities and can be performed on the ground, and those which require relatively little computational capability and can be implemented aboard the rover. This is extremely important in that the design of the micro rover is highly constrained in terms of its power, mass, and volume. As an example, the onboard CPU, Memory, and I/O electronics must not require more than 1.5 watts to operate and must fit within a volume of less than $300cm^3$. High performance computers which satisfy such constraints and are flight qualifiable (i.e., radiation hard, SEL immune) are not readily available and hence the algorithms must be simple enough to implement on an 80C85 class machine.

4.2 Command Cycle%

The process by which commands are generated on the ground, uplinked to the lander, and executed by the microrover is depicted in Figure 3. The steps indicated therein constitute a single rover command cycle. One rover command cycle will be performed each Sol with the command sequence being uplinked to the lander starting at approximately 7:00am (martian time), shortly after Earth rise. The earth must be in the field of view of the lander since it communicates directly with the ground as opposed to communicating through an orbiter.

An important constraint 011 the overall mission is that the lander can generate and store only enough energy to drive its high gain antennae for two hours each Sol. The plan is thus to have the lander telemeter data down to the earth twice per Sol. In the morning, the lander will telemeter data collected early that morning from the landers science instruments and engineering sensors as well as data collected by the rover the previous night (if night op-

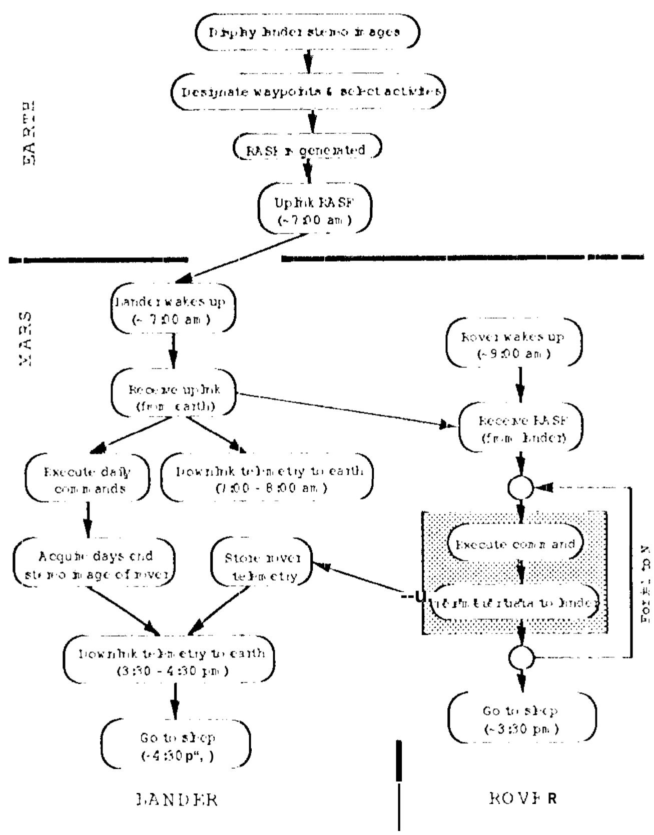

Figure 3: A microrover command cycle depicting the process by which a rover command sequence is generated on the ground, uplinked to the spacecraft, and executed by the microrover.

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GoTo-XY                  ; Navigate to waypoint, avoid obstacles
    X = 3.5 (m)          ; X coordinate of first waypoint
    Y = 2.1 (m)          ; Y coordinate of first waypoint
    T = 300 (sec)        ; Timeout (i.e., maximum travel time)
    ...                  ; additional command parameters
GoTo-XY                  ; Navigate to waypoint, avoid obstacles
    X = 4.2 (m)          ; X coordinate of second waypoint
    Y = 3.8 (m)          ; Y coordinate of second waypoint
    T = 500 (sec)        ; Timeout (i.e., maximum travel time)
                         ; additional command parameters
Acquire-Image            ; Take a picture
    Camera = R           ; Rear camera
    Exp = 1.25 (sec)     ; Exposure time
                         ; additional command parameters
Deploy-APXS              ; Deploy APXS
    Config : Soil        ; Soil sampling configuration
                         ; additional command parameters
Acquire-Spectra          ; Acquire an APXS Spectrum
    Integ = 60 (min)     ; Spectrum integration time
    Bnum = 1             ; Store in APXS memory bank 1
    .                    ; additional command parameters
Status                   ; Collect health and status data
                         ; additional command parameters
GoTo-XY                  ; Navigate to waypoint, avoid obstacles
    ...                  ; additional command parameters
ETC.
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Figure 4: Annotated Rover Activities Sequence File (RASF) containing several fundamental rover commands.

erations were performed). In the afternoon, the lander will telemeter data it has collected during the day, including days-end images of the rover, along with the data collected by rover. The uplink/downlink rate is approximately 600 bps.

In contrast, the rover and lander will communicate with one another throughout the Sol via UHF modems (9600 bps; 450-470Mhz) with the rover transmitting an average of 2 Mbytes/Sol. As indicated in Figure 3, the rover transmits data to the lander after each command is executed. The lander simply stores the data until it can forward it to the ground. In addition to reducing tile amount of onboard memory required, this strategy minimizes the amount of data lost if the rover suffers a critical system failure during the Sol.

4.3 Command Sequences

The locations through which the rover will travel and the activities that will be performed a specific sites are chosen by the experiment team based upon the results of previously collected data, the most recent images of the rover and surrounding terrain, and the relative importance of the experiments yet to completed. Once selected the operator uses the interactive capabilities of the rover control station to construct the actual command sequence to be uplinked to the rover via the lander. The resulting executable command file is called a Rover Activity Sequence File, or RASF. An example of an annotated RASF, or component thereof, is presented in Figure 4.

4.4 Navigation

The GoTo-XY command is the principle means for instructing the microrover to move from one waypoint to the next while simultaneously avoiding obstacles and hazards. As described, the execution of the GoTo XY command, along with the rest of the commands in a RASF, is performed completely autonomously. In addition, to the GoTo XY command, there are several other commands which can be used to reposition and/or reorient the vehicle. These "discrete-motion" commands, however, are intended for diagnostic purposes and do not invoke feedback beyond that of servoing the drive and steering motors to specified positions.

The implementation of the GoTo-XY command consists of three primary components. The first component is the dead-reckoning algorithm which is used to compute an estimate for the location (i.e., X-Y position and heading) of the microrover relative to the lander. The heading estimate and the current heading setpoint arc used by the low level servo system to control the vehicle's steering angle. The second component is the underlying navigation algorithm which simply drives the vehicle directly towards the specified waypoint. Ideally, if no obstacles and/or hazards arc present and the vehicle has perfect traction, the vehicle will travel along a straight line to the waypoint. The third component is the behaviors which utilize information from the onboard sensors to detect the presence of obstacles and/or hazards and generate steering/drive setpoints which override those generated by the underlying navigation algorithm. Once the vehicle 110 longer senses the presence of an obstacle/hazard and it has completed executing its avoidance maneuver, the behaviors return to generating a "null" output and the underlying navigation algorithm takes control of the vehicle.

The dead-rcckol]ills algorithm and the means for detecting and avoiding obstacles and hazards are described in the following sections.

4.5 Dead-Reckoning

The microrover's dead-reckoning algorithm combines the measurements obtained from the six drive wheel encoders, the three linear accelerometers, and the rate gyro to estimate the position and heading of the microrover with respect to the lander. The heading component is estimated using the readings from the rate gyro and accelerometers. The accelerometers, which also measure inclination directly, arc used to compensate the readings obtained from the rate gyro to account for changes in the orientation of the k'chicle's chassis. The compensated readings are then integrated to form the final heading estimate.

The vehicle's position is estimated by first computing the average of the number of degrees (i.e., number of counts) each wheel has traveled since the previous control cycle. The averaging reduces the errors associated with using a minimal subset of the wheel rotation measurements. The average wheel rotation is converted into downrange travel by multiplying it by the wheel radius. The downrange travel is then decomposed into the distance traveled along the lander's X and Y axes (i.e., ΔX and ΔY) based upon the current estimate of the vehicle's heading. Finally, the estimate of the vehicle's position is updated by adding ΛX and A}' to the current estimates.

The accuracy of the above estimates depends heavily upon the vehicle's kinematics, soil density, and wheel/tread design. In general, the estimates continuously accumulate errors. A means for bounding these errors, however, dots exist since the lander will image the rover at the end of each sol. When generating a RASF, the operator will fit a 3-1) graphic model of the rover to the actual 3-D image of the rover and extract the model's position in lander coordinates. This position estimate will be incorporated into the RASF and used to reset the onboard position estimate. The dead-rcckonil)g errors can thus be reduced to the accuracy of the lander's imaging capability so long as the rover can be seen by lander. Other techniques for reducing the dead-rccliollillg errors as the vehicle moves arc currently under development but arc beyond the scope of this paper.

4.5.1 Obstacle/Hazard Detection

The martian environment poses many potential threats to the safety of the microrover including large rocks, complex boulder fields, cliffs, ravines, escarpments, steep slopes, and dust pits, just to name a few. In response, the microrover has been equipped with a variety of sensors for detecting the presence **of** critical hazards. These sensors range from the simple potentiometers which measure the kinematic configuration of the mobility subsystem to the more sophisticated proximity sensing system which is comprised of 5 laser stripe projectors and 2 CCD cameras.

The sensors incorporated in the design have been chosen to overcome many of the sensing limitations which were experienced 011 earlier vehicles. For example, the IR proximity sensors on Rocky IV were limited to single point binary detection of obstacle presence. One such sensor was attached to the rocker-l)op;ic struts above each of the four outer wheels. Due to the sparsity of the measurements, their sensitivity to surface all.redo, and their movement relative to the vehicle chassis, these sensors where unable to detect the presence ofl cliffs and holes and frequently failed to detect obstacles directly in front of the vehicle. Consequently, the vehicle was susceptible to falling of a cliff, getting caught in a hole, and high centering.

To overcome these earlier limitations and to address other hazard conditions, the flight microrover contains an integrated proximity sensing system which includes two CCD cameras and five stripe projectors. The stripe projectors and CCDs arc mounted to the front of the vehicle just below the solar panel as indicated in Figure 2. The cameras have an extremely wide field of view, 1.7 radians in the horizontal direction and 1.4 radians in the vertical direction, and a resolution of 2.5 mrad/pixel.

The stripe projectors generate vertical planes of light which create visible stripes on the surface of obstacles and the terrain in front of the vehicle. When viewed by the cameras, each stripe appears as a ragged line due to the irregularities in the terrain. Since the cameras and stripe projectors arc all mounted along the same horizontal axis, these ragged lines cross each scan line within the image only once. The five projectors generate one stripe out over the Ti.gilt front R'lice], one out over the left front wheel, one out the center of the vehicle, and two stripes which arc projected diagonally out across the front of the vehicle.

The detection of the presence of hazards using this arrangement of CCDs and stripe projectors is based upon triangulation and thresholding. Triangulation is used to measure the range to an obstacle and or a surface patch upon which a light stripe has landed. Thresholding is then used to determine whether or not the range measurement signifies the presence of a hazard. For example, consider the task of looking for a hole or cliff in front of the right wheel. In this case, the right stripe projector is turned on and the right camera takes an image. Then a scan line is selected near the bottom of the image and filtered to locate the position at which the light stripe crosses the scan line. This position corresponds the angle at which the reflected light ray entered the lens. With this information and the known geometry of the stripe projector and camera, the range to the illuminated point is computed. This range is then compared to the range that one would expect to measure if the vehicle where sitting on a large flat surface. If the former is significantly greater than the latter, it indicates that the terrain drops off sharply and that a hazard exists. If it is less than the latter it indicates that the terrain is sloping upward. If the difference is very large it indicates that an obstacle, such as a rock, is immediately in front of the wheel.

When the vehicle is navigating, both the right and left cameras are used to sense for hazards and the stripe projectors are powered on and off in a preprogrammed sequence to insure that multiple stripes appearing within a single image can be properly disambiguated. In addition, four scan lines are typically used at the same time; one at the top of the image, two in the middle, and one at the bottom. The processing of multiple scan lines enables the system to look for hazards which lie directly in front of the vehicle as well as more distant hazards. On Mars, this proximity sensing and hazard detection system is designed to operate over a range of 10 to 50 cm. If required, the operating range can be increased by subtracting out the ambient light through simple image differencing. This would increase the spot detection SNR, which is approximately 3, by roughly two orders of magnitude.

A variety of other sensors are used to detect hazards. These include, for example, the accelerometers which measure vehicle inclination and provide an indication of whether or not vehicle is likely to tip over. They also serve to indicate which way the vehicle will slip traveling laterally along a steep slope. Contact sensors on the lower front edge of the belly pan serve as a safety net against the presence of belly height rocks which may have been missed by the proximity sensing system and could cause the vehicle to fatally high center. Contact sensors on the rim of the solar panel indicate that the vehicle has come too close to rock with overhanging protrusions. The bogey and differential position sensors indicate the presence of insurmountable obstacles and/or unexpectedly rough and potentially hazardous terrain.

A complete description of all the hazards which can be detected by the microrover is beyond the scope of this paper.

4.5.2 Obstacle/Hazard Avoidance

The microrover avoids obstacles and other navigation related hazards by invoking preprogrammed behaviors which override the default straight-line navigation algorithm. The particular behavior invoked depends upon which hazards have been encountered. For example, if one of the front contact sensors is depressed the vehicle is programmed to immediately stop, backup up, turn to one side, and drive forward a short distance. If no other hazards are present, the vehicle re-invokes the straight-line navigation algorithm and again starts heading directly towards the next waypoint. Designing behaviors which safely avoid all of the hazards can sometimes be quite tricky and the designers make frequent use of experimental results to assist them in tuning the behavior parameters (e.g., the amount to turn before moving forward). The greatest challenge, however, lies in determining what to do when more than one hazard has been detected. To avoid having to develop a large set of behaviors, each of which corresponds to a different possible set of hazard conditions, the overall behavior control algorithm contains a decision tree which determines which hazard is more important (i.e., which is more likely to cripple the microrover) and thus which behavior should be invoked first. Like the behaviors themselves, the decision tree is preprogrammed and constructed by the designers based upon a simple analysis of the vehicle's capabilities and failure modes.

The obvious advantage to behavior control is its computational simplicity. Based upon our prior experiences with Rocky III and Rocky IV, it is estimated that the final flight system will contain approximately 15-20 elemental behaviors which, in various combinations, can be used to respond to all of the hazards which are likely to exist, on Mars. If, however, the vehicle is unable to successfully reach a specified waypoint within a specified amount of time, and/or after having traveled a specified amount, it can simply stop and "phone home". At that point, the ground-based operator and experiment team can analyze the situation using the data collected during the vehicle's attempt to reach the waypoint as well as lander-based images of the rover. A new RASF can then be generated, uplinked to the rover, and used to "walk" the vehicle out of its current predicament. From a mission point of view, this approach constitutes a balance between the amount of autonomy which one can reasonably expect to incorporate into such a small and computationally limited vehicle, the immense cognitive skills of the systems' human operators, and the level of risk than can be reasonably assumed when dealing with multi-million dollar interplanetary mission.

5 CONCLUDING REMARKS

The MESUR/Pathfinder Mission will play an extremely important role in the evolution of interplanetary exploration. If successful, it will set the stage for the development of small, moderately-priced spacecraft capable of controlling sophisticated scientific instruments. In addition, it will demonstrate that robotic vehicles, like the one described in this paper, can successfully perform a wide range of new and exciting scientific experiments (e.g., the emplacement of instruments like the APXS against rocks which lie beyond the reach of a lander).

The task of designing a microrover for operation on Mars poses numerous challenges. Many of these arise from the characteristics of the martian environment, the most severe of which is thermal cycling. The heretofore unanswered questions about the properties of the martian soil also bring about numerous challenges.

In conclusion, it is hoped that the MESUR/Pathfinder microrover will provide the research community with valuable information to assist, in the design of future planetary rovers.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the contributions of each and every member of the MESUR/Pathfinder Microrover Design and Implementation Team. The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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